Journal of Electroanalytical Chemistry 903 (2021) 115871

Contents lists available at ScienceDirect

Journal of Electroanalytical Chemistry

journal homepage: www.elsevier.com/locate/jelechem

Review

Preliminary survey on cold fusion: It's not pathological science and may require revision of nuclear theory

Freire Luciano Ondir *, Andrade Delvonei Alves de

Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN/SP), Nuclear Engineering Center, São Paulo, Brazil

ARTICLE INFO

Keywords:
Cold Fusion (CF)
Low Energy Nuclear Reactions (LENR)
Lattice-Assisted Nuclear Reactions (LANR)
Lattice Confinement Fusion (LCF)
Anomalous Heat Excess (AHE)

ABSTRACT

Since 1989 the announcement of "cold fusion" by Stanley Pons and Martin Fleishmann, "cold fusion" field has been surrounded by controversy. After three decades, this field is alive and has produced thousands of publications, most in dedicated periodic and conferences. This work aims at checking whether "cold fusion" fits in pathological science traits. For each type of experiment and year, this work counted the distinct research groups results (success or failure). Experimental results from many research groups suggest that nuclear reactions in solids are more complex than fusion (it is not only fusion) and that they need energy triggers like background radiation, meaning chemical configurations alone do not seem to generate nuclear reactions. Some types of experiments present rising trends (the field does not fit in pathological science model) and have potential to bring disruptive technologies. If confirmed, experimental results will require revisions of accepted nuclear models.

Contents

* Corresponding author at: Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN/SP), Av. Professor Lineu Prestes 2242, 05508-000 São Paulo, SP, Brazil.
E-mail address: luciano.ondir@gmail.com (L.O. Freire).

https://doi.org/10.1016/j.jelechem.2021.115871
Received 17 May 2021; Received in revised form 8 November 2021; Accepted 9 November 2021
Available online 14 November 2021

1. Introduction

Before entering in the historical and technical aspects of cold fusion, some concepts need to be clarified. Fusion is a natural nuclear reaction that occurs in stars and makes a larger nucleus from two smaller ones. For light isotopes, it is exothermic, and different from fission, which uses elements that are rather rare in the universe, fusion uses the most abundant elements, like Hydrogen and Lithium. Current science knows only fusion occurring at extremely high temperatures, like those found in stars, as the Coulomb repulsion forces cannot be overcome without a considerable amount of energy. Yet, fusion is a dream because it would allow generation of cheap energy using abundant resources, even though it would need large and complex machines to deal with its temperatures and radiation. Another advantage is the absence of radioactive ash, as a fusion reactor would produce Helium atoms, along with neutron and gamma radiation. A more radical dream is to find a way to make fusion reactions without the need of heating matter to star temperatures, allowing the use of simpler machines. Even if radiation shielding would constrain the use to large machines, like containerships propulsion, a technology making fusion at temperatures below the melting point of high temperature alloys would make energy much cheaper. A golden dream would be to have clean nuclear fusion reactions, free from neutrons and gamma rays, that would allow even small machines like truck motors to be free from chemical fuels.

This golden dream is called “cold fusion”, and its realization, in optimistic views, would bring a new era of prosperity to humankind, as clean energy in large quantities would be within everyone’s reach. “Cold” means finding a solution to make nuclear reactions without heating atoms to millions of degrees Kelvin, using for instance, some sort of chemical configuration. “Fusion” means that the nuclear reactions are combinations of small nuclei (Hydrogen, Deuterium, Tritium) into larger atoms, like Helium. Therefore, “Cold Fusion” means to use a solution (chemical, cavitation, biological, magnetic, electric, etc) to combine Hydrogen isotopes. This dream has also other names, like Low Energy Nuclear Reactions (LENR), Anomalous Heat Effect (AHE). Other similar, but conceptually distinct ideas are Lattice Assisted Nuclear Reactions (LANR), which means nuclear reactions happen in a metal, but it is not necessarily “cold”, as one could use radiation to heat individual atoms. Further, it is not necessarily fusion, but could be some kind of other nuclear reactions, like alpha decay, Oppenheimer-Phillips stripping reactions, fission reactions. Like LANR is Lattice Confinement Fusion (LCF).

In a darker point of view, at least in the short term, such technology could bring a true nightmare of technological disruption, leading many enterprises to bankruptcy, causing mass unemployment. Countries adopting such technology would reduce cost of living and industrial production, possibly leading late adopters to mass enterprise bankruptcy, reduction of received taxes, unemployment, and social unrest. The economical unbalance would bring military unbalance, as military applications would appear faster than civilian applications, such unbalance could even make the current nuclear deterrence become obsolete, as ships could be equipped with powerful weapons. Launching satellites could become so cheap that countries could start the construction of orbital fortresses with powerful lasers, preventing the use of ballistic missiles. Economic and military unbalance could bring along wars and revolutions.

As both points of view are extreme and at the same time, realistic in face of the theoretical potential, “cold fusion” is naturally destined for controversy, more than other disruptive technologies which are not so obviously disruptive. As the potential of the field is stratospheric, scientists of related fields (such as hot fusion) become afraid their fields are going to lose priority and research funds, so there is an obvious potential conflict of interests. Therefore, as the stakes in this game are exceedingly high, people tend to be either a believer or a denier, a lover, or a hater, and perhaps truth lies elsewhere.

Stanley Pons and Martin Fleishmann announced in 1989 that they had obtained nuclear reactions in an electrolytic cell, meaning that the realization of the aforementioned “golden dream” was at hand. After a short excitement period, the field became controversial, and the press named the phenomenon “Cold Fusion”. Some research groups did not confirm the claims, some confirmed, and others had partial confirmation. The fact is none was able to generate useful results, on the other hand, intriguing facts were identified, but as they do not fit current models, mainstream scientists labeled those results as errors.

In fact, there are accounts of initiatives on this field before 1989, like Ivan Stepanovich Filimonenko, who created an apparatus to produce energy at a metal tube of 41 mm diameter and 700 mm long at 1150 °C. This apparatus used heavy water and an alloy containing Palladium. This concept started in late 1950s, and in 1962, Filimonenko filed an application for the invention “Process and installation of thermal emission”, but the State Patent Examination denied him because it believed nuclear fusion cannot happen at low temperature. Anyway, Filimonenko obtained support to build a demonstrator, that despite being successful the research was stopped in 1968 on grounds of “political disloyalty”. Later, in 1989, it was resumed, but only to stop again in 1990 with the collapse of Soviet Union [1].

Speri [2] had already demanded a patent of Helium production from hydrocarbon sparking but did not expose the invention to a larger audience [3]. Jones et al. [4] also presented neutrons from deuterated Titanium, yet in a much smaller ratio than Fleischmann and Pons [5]. Most research groups, after failing to obtain results in typically four-week experiments, gave up on further research. Other groups like NASA [6] and Oak Ridge [7], after having a partial success gave up. Most scientists, since 1989, took the stance that “cold fusion” field was “pathological science” like Huizenga [8], on grounds of three facts:

1 – Impossibility of overcoming the Coulomb barrier.
2 – Abnormal branching ratio between Tritium and Helium-3 paths, resulting in few neutrons.
3 – Absence of radiation, like gamma or X-rays.

Few research groups went on, finding difficulties in publishing their findings, researchers who did continue became virtually segregated from mainstream science. Fusion Technology kept publishing peer-reviewed works up to 2001, when George Miley retired. After Shanahan [9] pointed some potential errors in calorimetry, few other authors outside the field made critics or independent tests with negative results. Although works presenting conflicting results do exist in the field, today most authors agree on the existence of excess heat in absence of expected quantity of neutrons.

In short, the Cold Fusion field has two primary issues: partial reproducibility and lack of convincing explanation. However, for the unbiased reader, there is a fundamental question: is there some reality in the claims of the cold fusion field? If at least part of claims are real, given the advantages of "cold fusion", it is obvious that investment is needed immediately in the field before it is too late. However, if it is pathological science, one should avoid wasting resources on this field. Therefore, this work focuses in bringing forth facts about "cold fusion" research and identifying some trends in this field to verify if it meets the "pathological science" criteria.

Irving Langmuir introduced the "pathological science" concept during a 1953 colloquium at the Knolls Research Laboratory. The authors chose Langmuir's criteria for pathological science because they are simple and applicable to experimental research, being focused on practices. For instance, Carl Sagan's and Michael Shermer's criteria, explored by Storms [10], are focused on theories and ideas. In cold fusion field, many authors simply perform experiments and present unexpected results without giving an explanation, so Langmuir's criteria fit better to existing literature.

The authors have never done experimental work and cannot state that any of those types of "cold fusion experiments" actually have positive results. According to Irving Langmuir, the phenomenon of "pathological science" has the following characteristics:

a. A causative agent of barely detectable intensity produces the maximum effect observed, and the magnitude of the effect is substantially independent of the cause intensity.
b. The effect is of a magnitude that remains close to the limit of detectability, or many measurements are necessary because of the extremely low statistical significance of the results.
c. There are claims of great accuracy.
d. Fantastic theories contrary to experience are suggested.
e. Criticisms are met by ad hoc excuses.
f. The ratio of supporters to critics rises and then falls gradually to oblivion.

2. Assumptions

This section lists a series of assumptions made to make this work applicable for scientific community:

1 – Experimental results do not need to fit in current models: the role of scientists is to make models fitting reality and not deny experimental results.
2 – Experimental errors do occur, so only when more than one individual or group confirms the results, information becomes more reliable.
3 – Confirmation bias does exist, meaning that many results from a single individual or group does not add to the information reliability.
4 – Non-deterministic phenomena exist, meaning there may be different results for the same experiment, requiring many tests to get a statistically significant description of phenomenon.
5 – Success of failure of an experiment is a subjective judgment and this work report the subjective stated opinion of research groups, not what the authors of this work believe to be the objective truth.
6 – Langmuir's criteria for pathological is the best for this case because it focuses on experimental science and this work focuses on the experimental part of "cold fusion" field.
7 – reported failures are from non-supporters and successes come from supporters.

3. Method

1. This work adopted the following steps to apply the Langmuir criteria, as Fig. 1 shows:
2. Identification of main sources of information in the field.
3. Identification of works already done in the field or similar fields.
4. Skimming of experimental works to identify the main types of experiments appearing over time.
5. Identification of research groups related to each work.
6. Selection of main types of experiments, as there are so many that a single article could not present all of them and independent groups do not confirm many.
7. For each type of experiment, presentation of the number of yearly results per research group, divided in two situations: confirmations of any evidence of nuclear reaction for the type of experiment or failure to confirm any evidence of nuclear reactions. In the criteria for success, authors included not only excess heat, but also any evidence of nuclear reactions, like charged particles, element transmutations, isotopic changes from natural ones, gamma radiation, neutron radiation, radiofrequencies, hot spots, micro-explosions.
8. Application of a trend line by linear minimum squares curve fitting on the yearly number of successful group-experiments to identify objectively if the subfield in rising or vanishing (one of the characteristics of pathological science according to Langmuir), although interest in the field may disappear even if it is not pathological science. For instance, the effect may be real but proven inutile, other field becomes much more attractive, no further questions remain open or further research is too expensive. But, if any of the subfields is growing or market products appeared using the findings of the field, cold fusion is probably not pathological science.

4. Development

4.1. Identification of the main sources of information in the field

The most recent works are in the Journal of Condensed Matter Nuclear Science (JCMNS) whose volumes are available at https://iscmns.org/publications/jcmns/volumes/. The site www.lenr-canr.org provides interesting resources, like most proceedings of International Conference on Cold Fusion (ICCF). The American Institute of Physics hosted a proceeding of a conference on Anomalous Nuclear Effects in Deuterium/Solid Systems in 1990 (AIP 228). India has a research center in Trombay (Bhabha Atomic Research Center – BARC), which produced many works on the field with many successful experiments, and many are assembled in a single volume "BARC-1500, available at https://lenr-canr.org/wordpress/?page_id=463. Fusion Technology published many works in the period from 1989 to 2000 when George Miley retired. Additionally, the ancient articles reporting failure to replicate cold fusion phenomena received special attention. Cold Fusion journal articles were neglected because authors could not find most of them. Authors also included articles from LENR-CANR.org library, which had about 4737 entries, including magazine articles, newspaper articles and interviews. However, only journal and conference articles presenting new empirical results counted for this work.

There were also many conferences named "International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals", but authors did not find most of the proceedings, except for the 8th and 12th. Other sources, like the books "Cold Fusion: The History of Research in Italy" and "Low-Energy Nuclear Reactions Sourcebook" were also considered.

It was not possible to find and consider every work because authors could not find them or they were in other languages, like Russian or Japanese. In any case, authors found the downloadable links to the proceedings of Japan Cold Fusion (JCF) society meetings, from JCF-4 to JCF-20 at the site http://jcfrs.org/proc_jcf.html. The proceedings of the Russian Conference on Cold Transmutation of Nuclei of Chemical Elements and Ball Lightning (available at http://lenr.seplm.ru) were included in the analysis, except by the 23rd conference (not found). Nevertheless, it seems this work found most of the research groups and perhaps most of the important experiments, which seemed to be present in more than one publication.

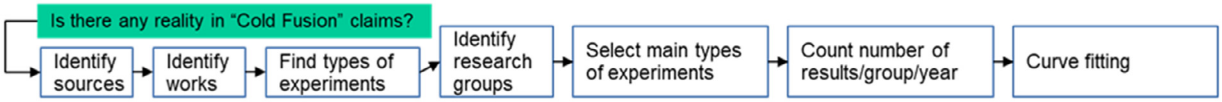

Fig. 1. Graphical representation of the adopted method.

Authors also verified the works present in more than one database, reducing the duplication of records and adopted a metric (number of research groups instead of number of works) that is robust to record duplication (and to various publications for a single experiment).

4.2. Identification of works already done in the field or similar fields

Thousands of articles were listed in a table with authors, title, year, and research group. This database became the base of subsequent analysis. This work neglected articles in field proposing theoretical models or showing experiments on adjacent non-nuclear aspects, like metallurgy, deuterium solubility, conductivity.

4.3. Skimming of experimental works to identify the types of experiments appearing over time

The experiments became more diversified over time, starting with Palladium-Deuterium and Titanium-Deuterium systems and adding Nickel-Hydrogen, Tungsten-Hydrogen, Palladium-Hydrogen systems. Works involving other types of experiments also appeared, like cavitation induced fusion, piezo fusion, exploding wires, and biological transmutations. For a given system, many subtypes of experiments appeared over time, starting with electrolysis and gas loading, and adding glow discharge, plasma electrolysis, and high-pressure gas loading. Furthermore, for a given subtype of experiment, there are many types of triggering methods to improve repeatability, like laser application, magnetic field, electric field, X-ray radiation, gamma radiation, neutron radiation, pressure variations, temperature variations, electric current variations, co-deposition, and nanoparticles.

4.4. Identification of research groups related to each work

Many of the thousand works were produced by a few hundreds of research groups, which faithfully kept a steady scientific production in the field. Given the assumption of confirmation bias, it is fundamental to know how many independent groups reported success or failure in finding nuclear reactions evidence for each type of experiment. Every researcher that never presented a "cold fusion" work before is added to an existing group if any co-author presented a work in the field before. If none of the authors presented anything before, a new group is added. If there are co-authors of more than one pre-existing group, the work is assumed to belong to the group of the first author (each work belongs to only one group).

4.5. Selection of main experiment types

There is a large diversity of experiments, a detailed analysis of each subtype and, for each subtype, the analysis of each triggering method, would be too lengthy for an article. The authors judged that for a reader outside the field, who for now are the vast majority, an analysis per type would have great value. Even for people in the field such analysis may be relevant to direct research strategy. First, it is possible to classify experiments by the combinations of materials, like Palladium-Deuterium or Titanium-Deuterium. For each combination of materials, there are many possible subtypes, like electrolysis, glow discharge or gas loading, but this work neglected the subtype to avoid too much complexity for a reader that does not know this field. There are also some types of experiments that are not related to a specific material, like cavitation, piezo fusion and use of biological organisms to induce nuclear reactions. Such procedures seem not to depend on a specific set of materials, so this work adopted those methods as subfields to check the trend. Therefore, this work presents only analysis for the following types of experiments: Palladium-Deuterium, Titanium-Deuterium, Nickel-Hydrogen, Tungsten-Hydrogen, cavitation, piezo fusion and biological.

4.6. Presentation of evolution of experimental groups working in the field over time for each type of experiment

For each type of experiment, for each year, this work counted the distinct research teams publishing positive results (finding at least partial evidence of nuclear reactions not predicted by current accepted models) and the teams reporting negative results (no evidence of nuclear anomalies). For this count, this work considered the opinion of authors of each article and not the data presented. For instance, Fralick et al. [6] stated there are no nuclear reactions because they measured no neutrons, although data shows anomalous excess heat. This work considered this 1989 article as a negative result, even though data indicates a positive result confirming other research groups' findings of neutron radiation near background levels. Objective truth is this same research group presented a more recent work [11] showing nuclear transmutations in the equipment used in 1989 experiments, meaning from the point of view of objective truth, both experiments seem to be positive. However, this work, as per assumption "5″, reports the subjective opinions expressed in the article conclusion, not an analysis of raw data from every research group.

The count considered only one work for each team per year for each experiment type and result (successful or unsuccessful) because it seems the teams tend to publish the same experiment more than one time, for instance, in two conferences and one journal. If a given team produced two distinct experiments in the same year, the second experiment with the same type of result (successful or unsuccessful) was neglected. Conversely, if a team made an experiment and published data in three different years, this work counted one for each year.

5. Results

This section presents the results for each step. For the total articles found, this work listed a total of 5249 publications, including conference articles, conference presentations, journal articles, and patents. Amongst those, 2202 are experimental works reporting results of experiments, being 1921 successful and 281 unsuccessful.

In total, there are 375 distinct research groups involving 3460 researchers. There is, indeed, cooperation between research groups, but they are rather rare, most work is done by isolated groups.

5.1. Systems of combinations of nuclides (Metal plus Hydrogen isotope)

5.1.1. Palladium-Deuterium system

The most popular type of experiment is the Palladium-Deuterium system, whose evolution is presented in Fig. 2, where one can note a gradual reduction of research groups over the years (as the trend line shows). One can note that only in 1989, were the unsuccessful groups majority, and unsuccessful attempts became increasingly rare. Explanations for this fact may be:

Fig. 2. Results for Palladium-Deuterium systems.

a. Researchers that insisted in this subfield learned how to improve repeatability and taught other research groups.
b. A group of researchers was “tricked into false results by subjective effects, wishful thinking or threshold interactions” and kept publishing works.

This subfield involves a large set of types of experiments including, but not limited to, glow discharge, electrolysis, gas loading and ion beam. An important contribution for this system is the work of Irina Savvatimova group [12], which employed glow discharge in deuterium low-pressure atmosphere using Palladium cathodes. They found excess heat, transmutation of Palladium and Deuterium into an array of nuclides, both smaller and larger than Palladium, X-rays and a strange radiation that makes surprising tracks on X-ray films.

Even though the number of works is decreasing, the results are becoming more repeatable and significant, with large quantities of excess heat, showing an apparent progress in mastering this Palladium-Deuterium system [13].

5.1.2. Titanium-Deuterium system

Another popular system was Titanium-Deuterium, which got less and less attention over time (Fig. 3), although neutron generators based on Deuterium-Deuterium fusion in Titanium lattice have been at market for some years already [14]. It is interesting to note that for this system, more recent works out of the “cold fusion” field indeed found an enhancement of fusion reactions in metal lattices [15]. Therefore, there is an apparent paradox: despite confirmations and practical applications, Titanium-Deuterium systems are losing appeal in the “cold fusion” community. Important contributions were the works of the Steven Jones group [4] and Urutskoev group [16].

5.1.3. Nickel-Hydrogen system

An apparent emerging type of experiment is the Nickel-Hydrogen system, which started in 1990 and is increasing over time, as shown in Fig. 4. Authors claim that repeatability is good, energy produced is also larger than in other systems, some patents in Europe exist for this kind of system. This subfield seems to be currently the most popular and presents strongest growth in numbers of research group’s participation, including currently 70 research groups. About 52 research groups reported only successes, 10 reported mixed successes and failures and 8 reported only failures in obtaining anomalous nuclear reactions. Perhaps the lower cost of materials, large heat generation and easier replication in this type is causing research groups to abandon research on Palladium-Deuterium and Titanium-Deuterium systems.

5.1.4. Tungsten-Hydrogen system

Another less explored, but growing, subfield is the Tungsten-Hydrogen system, which is also more recent, as shown in Fig. 5. This work found 13 distinct teams presenting results in this subfield and only 3 failed attempts to obtain nuclear reactions. It is important to note that the same research that reported a failure in 2005 later presented three successful experiments in 2006, 2007 and 2009. Therefore, although there are reports of failed attempts in literature, this work found only one research group reporting only failures in this subfield.

5.1.5. Carbon and Hydrogen/Deuterium systems

The authors also found eight research teams reporting results for Carbon and Hydrogen/Deuterium isotopes, although this field seems to be stable or vanishing over time, without a definite trend. Fig. 7 presents experiments of gas loading, ion beams and electrolysis for Carbon-rich materials (charcoal, graphite, phenanthrene, grease).

5.2. Other techniques (Cavitation, Piezo-fusion, Biological)

5.2.1. Cavitation method

Cavitation-induced nuclear reactions have a stable number of articles over time, as shown in Fig. 7, involving eleven distinct research teams. This subfield involves many distinct types of experiments using

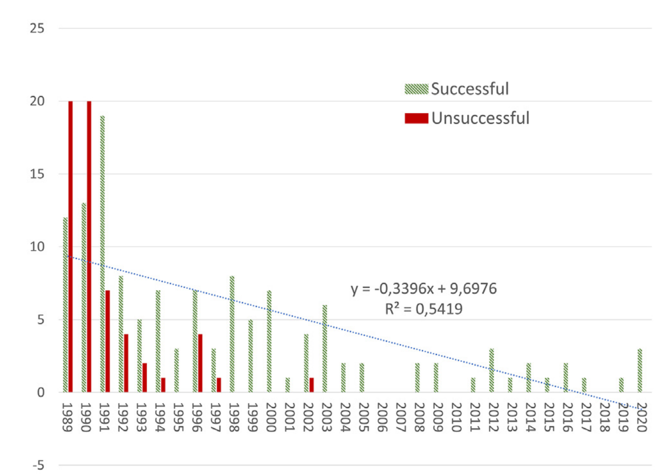

Fig. 3. Results for Titanium-Deuterium systems.

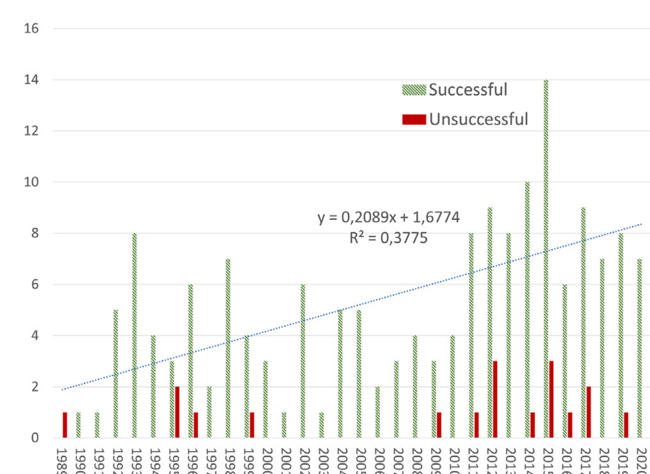

Fig. 4. Results for Nickel-Hydrogen systems.

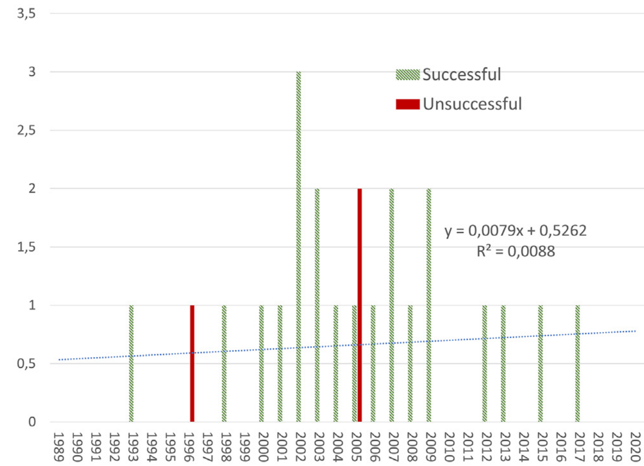

Fig. 5. Results for Tungsten-Hydrogen systems.

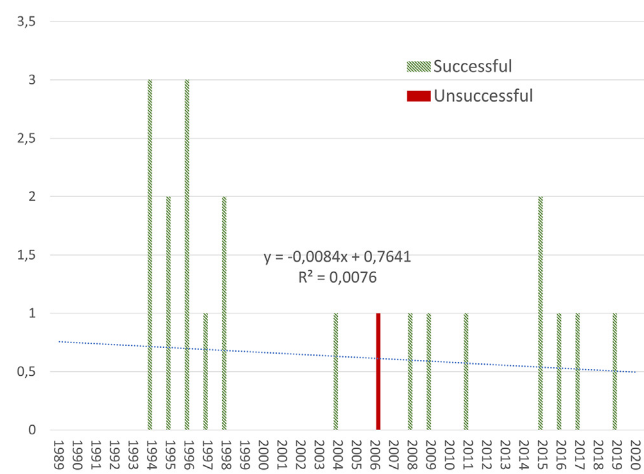

Fig. 6. Results for Carbon-Hydrogen/Deuterium systems.

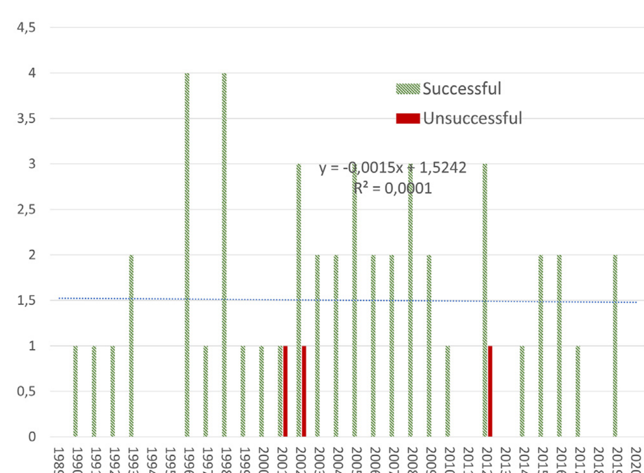

Fig. 7. Results for cavitation experiments.

cavitation to induce or increase the rate of nuclear reactions. They include:

a. Enhancement of nuclear reactions on liquid Lithium metal under Deuterium beam bombardment.
b. Palladium sheets under heavy water cavitation.
c. Cavitation in water jets.

It is interesting to note that authors found few works reporting a failure to reproduce results, which may be because the replication is easy, so most tentative were crowned with success.

5.2.2. Biological method

The authors found eight distinct teams reporting results of elements transmutation caused by biological processes. This subfield, besides explaining some isotopic anomalies in living beings, also proposes the use of bacteria for treating radioactive waste. This subfield has a patent in Russia and, although small, has increasing tendency, as Fig. 8 shows. An important contribution about this technique is the work of Vysotsky [17].

5.2.3. Piezo-fusion method

Finally, there are the piezo fusion experiments, which is the use of mechanical stress in solids to induce nuclear reactions. The authors found six distinct research teams, although works in this subfield are less numerous, but with tendency of increase, as Fig. 9 shows.

6. Discussion

This review of works done in the last thirty years may have overlooked an important piece, also papers in other languages than English may have been overlooked. However, an incomplete but wide overlook at the field may still be valuable. The authors believe it is unlikely that any number of missed works would change the general shape of evolution in time of subfields.

Readers may find important to know how many groups reported works for the complete cold fusion field, not only for the subfields described above. For instance, Bazhutov's group made a large set of experiments that do not fit in any of the system or techniques, but have significant value, like Bazhutov et al. [18]. Fig. 10 indicates that the number of groups presenting works in the field seems to be slowly fading after a peak in the nineties. However, in the last 20 years, the number of active groups seems to be quite stable and, considering the loss of interest in some subfields and emergence of other subfields, it seems that the field is not fading away.

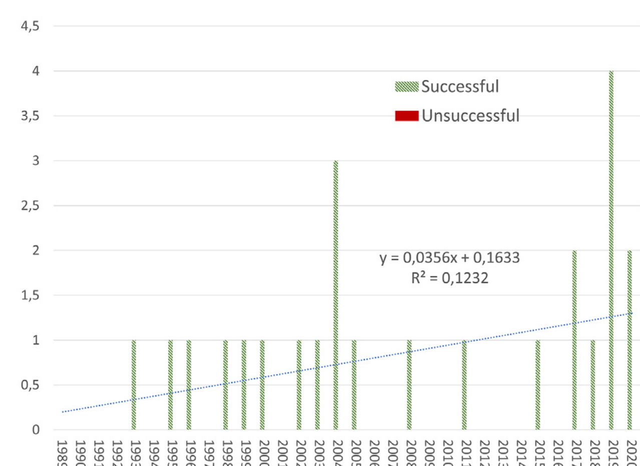

Fig. 8. Results for biological experiments.

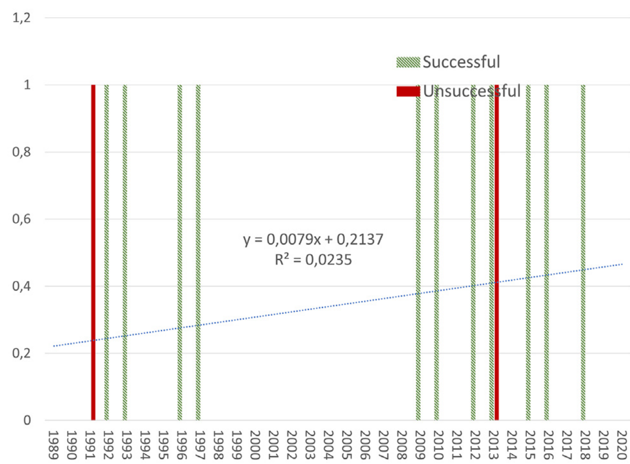

Fig. 9. Works presenting results for piezo fusion.

Fig. 10. Total research groups presenting results for cold fusion field per year.

A potential flaw of this method is the under-reporting of unsuccessful experiments, where researchers seek to find something that works and perhaps most report nothing when an experiment does not produce the expected result. However, in modern research organizations, researchers need to justify their time and spent resources, resulting in the publication of results, regardless of the success or failure of the intended goals. Therefore, perhaps under-reporting of failures is more applicable to individual researchers or private companies than to research organizations, meaning that this issue is related to a part of the effort and should not invalidate this study. The number of failures is not used in the conclusions because the Langmuir criteria is about the ratio of supporters falling to oblivion, so what matters for the criteria is whether the number of supporters is falling into oblivion or not, assuming that:

A. failures are from non-supporters; and
B. successes come from supporters.

Relying on the investigators' opinion of success or failure avoids the difficulty of reaching conclusions about results independently in this paper. The downside is this method presents the data from experiments interpreted as negative results, which are, in fact, positive just because of a negative opinion of skeptical researchers who wrote the article. Conversely, the opposite is also true, as negative results are presented as positive because the authors are believers in the phenomenon.

Another potentially interesting aspect is the diversity of experiments evolved over time (Fig. 11), and again, there was a peak in the mid-nineties and after that, the community seems more focused in a smaller set of experiments.

This work does not provide a deep meta-analysis like those made by Cravens and Letts [19] or Johnson and Melich [20], but a more general view of the field for people not familiar with "cold fusion". In the criteria for success, authors included not only excess heat, as many authors did, but also any evidence of nuclear reactions, like charged particles, elemental transmutations, isotopic changes from natural distributions, gamma radiation, neutron radiation, radiofrequencies, hot spots, and micro-explosions. For instance, in BARC studies, researchers chose not to look for excess heat but for nuclear transmutations, neutrons and radiation because that would be much easier to detect. Therefore, anytime a work reports something different from the expected (pure electrochemical or chemical reactions), this works considers it a success. For articles that state that nothing unusual or explain apparent nuclear reactions (somehow declare that unexpected effects are artifacts), this work counted a failure.

Ironically, many authors reported lighter elements in Palladium after excess heat events, making it implicit that Pd-D systems undergo fission processes, as surveys show [21,22]. Nobody has yet presented a universally accepted model explaining such fission reactions, but the production of lighter elements may be an answer to critics like Huizenga [8]. Current models predict that the fission of Pd requires proton energies of 30 MeV, so the processes in bulk metal are unknown yet ion beam experiments have already verified that Deuterium-Deuterium fusion cross-section in metals are larger [15]. A consequence is that Pd-D systems, except for military applications, are probably not going to be economically interesting because Palladium costs per kilogram is too high.

Some researchers, in the cold fusion field, however, view the cost of materials as very low in comparison to the value of the produced energy. Furthermore, it is quite possible that cold fusion is like a catalytic effect, in which the material is not consumed, except for hydrogen, which is abundant. If both assumptions are correct (large energy for materials cost and only Hydrogen is consumed), the importance of cost of materials are greatly reduced.

Another aspect is that some teams that abandoned cold fusion research in past are now returning to the field, like the team of NASA. NASA states their research is about Lattice Assisted Nuclear Reactions, as their experiments use deuterated metals under 2–3 MeV photon irradiation to trigger fusion events [23,24,25]. NASA also has partners

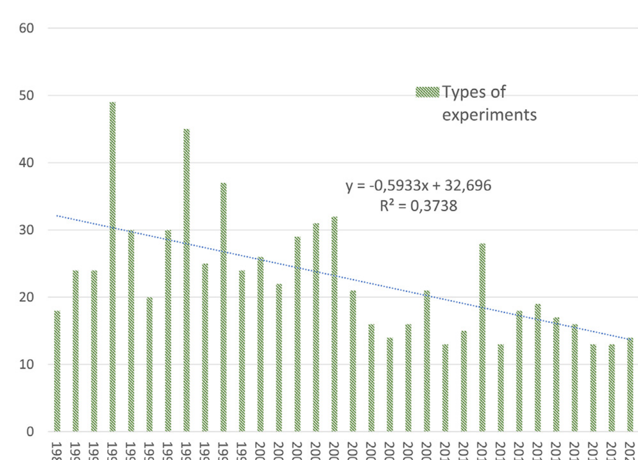

Fig. 11. Total research groups presenting results for cold fusion field per year.

working on an architecture of space propulsion [26] using co-deposition of Palladium and Deuterium, which is patented (US Patent 8419919).

In the cold fusion field, the causative agent is not agreed by all research teams, including, but not limited to background radiation [27], electric stimulation [28], laser stimulation [29], magnetic fields or electrostatic fields [30], temperature [31], pressure variations [11]. Those agents are quite measurable and results correlate (but not perfectly) with results.

In the beginning, many authors did not use any triggering method and reported extremely low effects requiring long time measurements [32], however it was not a general rule, like experiments of BARC [33]. The opinion of Shani et al. [27] is background radiation acted as a triggering agent, so experiments like those of Anderson and Jones [32], protected from background noise would have low results, if any. Experiments that are more recent employ one or more of the above-mentioned triggering methods and obtain large effects.

This work ignored theories and concentrated in experiments but claims and great accuracy and fantastic theories are present in the publications, although many researchers limit to publish experimental results without giving explanations, like NASA [11]. A plausible theory could be that proposed by Parkhomov [34].

This work also did not analyze systematically the way research groups answer to criticisms but found some works presenting explanations for some failed replications, like Anderson and Jones [32] and Cravens and Letts [19].

About the ratio of supporters, one can observe from Figs. 2–9 that the number of supporters is not necessarily falling, but new teams are entering in the field, depending on the subfield.

As a concluding remark about the pathological science characteristics, one may find that cold fusion field does not fit very well in all of them. Particularly for the evolution of supporters over critics, except for the Palladium-Deuterium and Titanium-Deuterium systems subfields, the number of supporters is increasing or stable.

In the beginning, most works concentrated on electrolysis or gas loading experiments on Palladium or Titanium. Over time, new kind of experiments appeared, like glow discharge experiments, plasma electrolysis, molten salt electrolysis, ion beam bombardment, use of bacteria for reduction of radioactivity, fusion by mechanical waves, and use of cavitation. In addition, the kind of measurements also started to diversify, going far beyond the neutrons, radiation, Tritium, Helium, and heat measurements. For instance, verification of isotopic shift or appearance of new elements became popular as well as detection of charged particles by plastic detectors (CR-39).

This field brought a surprise, however, in the discovery of Ni-H systems, which according to Levi et al. [35], changes metals isotopic distribution and consumes Hydrogen. At high temperatures (more than 1000 °C), experiments indicate stable operation, and many research groups of distinct countries have already confirmed this observation. Such temperatures allow highly efficient thermodynamic cycles, for instance in a Brayton cycle. Hydrogen is the most abundant nucleus in universe and Nickel is not very abundant but is not exceedingly rare and could be reused after burning. Therefore, Ni-H systems can be called “cold fusion”, yet they may involve nuclear reactions at MeV range, meaning it happens in metal lattice, but may not be “cold”. Experiments also report that such reactions do not emit MeV gamma radiation (many works report radiation in range of hundreds of keV), so there is no need for large shielding, allowing small machines to become nuclear powered. Analysis of ashes has not found radioactive isotopes, so treatment of radioactive waste is not needed.

Evidently, all those experiments work with unknown physics and there is no evidence that scientists may find some physical law that prevents us of finding a way to explore Ni-H systems. However, Andrea Rossi and Francesco Piantelli have already patented heat generators based on Ni-H (sometimes adding Lithium and Aluminum). Andrea Rossi claims he will start selling either services or machines soon in his website (https://www.ecat.org/). The experiments and demonstrations by Andrea Rossi, particularly the interactions and lawsuit with Industrial Heat, have become controversial within the cold fusion field. The authors find it is important to present public facts from an historical point of view, even though scientific value of certain claims may be questionable.

Therefore, Ni-H systems burn Hydrogen in a machine at temperatures near metal melting point without generating MeV radiation or radioactive byproducts. In fact, this could be yet better than the initial “golden dream” of Pd-D as Palladium is more expensive than Nickel and so does Deuterium compared to Hydrogen.

Another evidence that the field of cold fusion is not fading away is that lately, there has been appearance of new funding for cold fusion, like:

- NEDO project (2015–2017), funded by Japanese government.
- Google initiative starting in 2015.
- Nano-Metal Hydrogen Energy (MHE) in 2018–2020, funded by Japanese government.
- Hermes project (https://hermesproject.eu/) starting in 2020, funded by the European Union.
- Clean Energy from Hydrogen-Metal Systems (CleanHME) starting in 2020, funded by the European Union’s Horizon 2020 research and innovation program.

Without experiments it is impossible to know for sure whether cold fusion claims are true or not, but as Berlinguette et al. [36] pointed out, science is not a zero-sum game. In this field, much science still to be done may bring unexpected results, even if a newcomer to the field cannot replicate some type of experiment. For instance, Berlinguette et al. [36] reported failure in some experiment’s replication but the same team (funded by Google) found that neutron yields in deuterated Palladium for ions with less than 2 keV are two orders of magnitude larger than current models predict [37]. Such discoveries suggests that fusion in deuterated metals may be easier than current models predict. Assuming the growing trends in cold fusion field bring technologies to the market, given the long technology development cycles, it seems certain that late adopters would have difficulties to survive facing competition with early adopters. Energy is the foundation of all economy, and cheaper energy means cheaper products, improving competitive advantage of early adopting countries. Assuming current export restrictions will also apply to those technologies, countries procrastinating in starting the development of such technologies will experience a period of economic decline. This period may last 10–20 years, as development and mass production take long times, but nevertheless being enough to bring geopolitical transformations.

Last, but not least, one may question why businesspersons are not in such a disruptive field if it may bring them such huge profits. They would not care whether scientists agreed or not, but only if it works or not, therefore the absence of private investment in the field could be a proof that all the positive cold fusion results are just delusional pathologic science. The authors point that Industrial Heat LLC is an enterprise working with cold fusion and it has two patents and seven applications in the field [38]. This enterprise reached almost one billion dollars valuation in 2019 [39] and most of its applications are in the last two years. It is intriguing because, in recent years, US Patent Office typically refused cold fusion or “LENR” on grounds it does not work. Yet more intriguing are the applications of two LENR patents by Airbus (US20170025191, US20170022055) in 2017 and the report by a Boeing laboratory considering Ni-H LENR reactors for a new generation of aircraft [40]. Upon seeing such facts, one may surmise that corporate people do make mistakes, on the other hand it is a fact that some businesspersons are not staying out of the field in recent years.

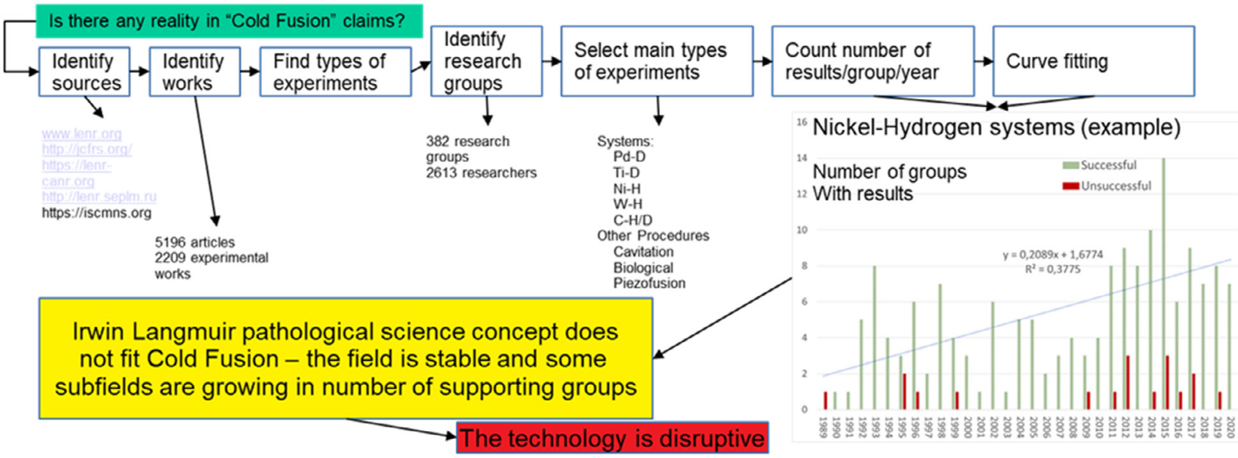

Fig. 12. Graphical abstract.

7. Conclusions

Despite the appearance of products using knowledge obtained in cold fusion research of Palladium-Deuterium and Titanium-Deuterium systems, they are vanishing trends in cold fusion field. Other types of experiments have a growing trend, particularly the Nickel-Hydrogen systems, which suggests the field is not pathological science. Apparently, the initial explanations for the excess heat phenomenon (chemical inducement of nuclear reactions without neutrons) were flawed, but many research groups replicated cold fusion experimental results. Fig. 12 presents the graphical abstract of this work.

The authors did not find a universally accepted model for the phenomena. However, if experimental results are real, current nuclear theory will require revision. Further, even without a theory, people may use the observed phenomena to make disruptive technologies by trial-and-error methods.

This work suggests to the reader two questions: first, whether the golden dream of the fusion is approaching our time; second, whether this is a dream or a nightmare. In case cold fusion becomes a reality, perhaps the answer to the second depends on the time that technology development starts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelechem.2021.115871.

References

[1] Y.L. Ratis, Controlled Fusion or Cold Fusion? A drama of ideas (in Russian), SSC RAS, Samara, 2009.
[2] O. Speri, Producer of controlled thermonuclear energy of hydrogen and its isotopes, Patent IT1024274B 20 (1974) 06.
[3] J.O. Bockris, Priority in Nuclear Reactions in the Cold, J. Condens. Matter Nucl. Sci. 7 (2012) 32–34.
[4] S.E. Jones, E.P. Palmer, J.B. Czirr, D.L. Decker, G.L. Jensen, J.M. Thorne, S.F. Taylor, J. Rafelski, Observation of cold nuclear fusion in condensed matter, Nature 338 (6218) (1989) 737–740.
[5] M. Fleischmann, S. Pons, Electrochemically induced nuclear fusion of deuterium, J. Electroanal. Chem. Interfacial Electrochem. 261 (2) (1989) 301–308.
[6] G. C. Fralick, A. J. Decker and J. W. Blue, “Results of an attempt to measure increased rates of the reaction D-2 + D-2 yields He-3 + n in a nonelectrochemical cold fusion experiment,” Cleveland, 1989.
[7] C. D. Scott, J. E. Mrochek, E. Newman, T. C. Scott, G. E. Michaels and M. Petek, “A Preliminary Investigation of Cold Fusion by Electrolysis of Heavy Water,” Oak Ridge, 1989.
[8] J.R. Huizenga, Cold Fusion: The Scientific Fiasco of the Century, 2nd ed., Oxford University Press, Pennsylvania State University, 1993, p. 318.
[9] K.L. Shanahan, A systematic error in mass flow calorimetry demonstrated, Thermochim. Acta 387 (2) (2002) 95–100.
[10] E. Storms, T. Grimshaw, Judging the Validity of the Fleischmann-Pons Effect, J. Condens. Matter Nucl. Sci. 3 (1) (2010) 9–30.
[11] G.C. Fralick, R.C. Hendricks, W.D. Jennings, T.L. Benyo, F.W. VanKeuls, D.L. Ellis, B.M. Steinetz, L.P. Forsley, C.E. Sandifer, Transmutations observed from pressure cycling palladium silver metals with deuterium gas, Int. J. Hydrogen Energy 45 (56) (2020) 32320–32330.
[12] A.B. Karabut, Y.R. Kucherov, I.B. Savvatimova, Nuclear product ratio for glow discharge in deuterium, Phys. Lett. A 170 (4) (1992) 265–272.
[13] T. Mizuno, J. Rothwell, “Increased Excess Heat from Palladium Deposited on Nickel,” in *Proceedings of 22nd International Conference for Condensed Matter Nuclear Science (ICCF-22)*, Assisi, Italy, 2019.
[14] IAEA, “Neutron Generators for Analytical Purposes,” VIENNA, 2012.
[15] F. e. a. Raiola, “Enhanced d(d,p)t fusion reaction in metals,” *The European Physical Journal A - Hadrons and Nuclei volume,* vol. 27, pp. p. 79-82, March 2006.
[16] L.I. Urutskoev, V.I. Liksonov, V.G. Tsinoev, Observation of Transformation of Chemical Elements during Electric Discharge, Annales de la Fondation Louis de Broglie 27 (4) (2002) 701–726.
[17] A.A. Kornilova, V.I. Vysotskii, Synthesis and transmutation of stable and radioactive isotopes in biological systems, RENSIT 9 (1) (2017) 52–64.
[18] Y.N. Bazhutov, A.I. Gerasimova, V.V. Evmenenko, V.P. Koretskiy, A.G. Parkhomov, Y.A. Sapozhnikov, Calorimetric and radiation diagnostics of water solutions under intense light radiation, J. Condensed Matter Nucl. Sci. 19 (2016) 10–17.
[19] D. Cravens, D. Letts, “The enabling criteria of electrochemical heat: beyond a reasonable doubt,” in *Proceedings of 14th International Conference on Condensed Matter Nuclear Science (ICCF-14)*, Washington, D.C, 2008.
[20] R. Johnson, M. Melich, Weight of Evidence for the Fleischmann-Pons Effect, in *ICCF-14 International Conference on Condensed Matter Nuclear Science*, 2008.
[21] G. H. Miley, “On the Reaction Product and Heat Correlation for LENRs,” in *8th International Conference on Cold Fusion*, Lerici, Italy, 2000.
[22] G. Miley and P. Shrestha, “Review Of Transmutation Reactions In Solids,” in *10th International Conference on Cold Fusion*, Cambridge, MA, 2003.
[23] T.L. Benyo, B.M. Steinetz, A. Chait, L.P. Forsley, V. Pines, M. Pines, “EVIDENCE OF THE ELECTRON-SCREENED OPPENHEIMER PHILLIPS REACTIONS 162Er(d, n) 163Tm OR 162Er(p, γ)163Tm IN DEUTERATED MATERIALS SUBJECTED TO A LOW-ENERGY PHOTON BEAM,” in *9th International Particle Accelerator Conference, IPAC2018*, Vancouver, BC, Canada, 2018.
[24] T. e. a. Benyo, “Investigation of Deuterium-Loaded Materials Subject to X-Ray Exposure,” Cleveland, Ohio, 2017.
[25] B. M. Steinetz and e. al., “Novel Nuclear Reactions Observed in Bremsstrahlung-Irradiated Deuterated Metals,” Cleveland, 2020.
[26] L. P. Forsley and P. A. Mosier-Boss, “Space Application of the GeNIE HybridTM Fusion–Fission Generator,” *Journal of Condensed Matter Nuclear Science,* p. 95–118, Vol. 29 August 2019.
[27] G. Shani, A. Brokman, C. Cohen, A. Grayevsky, “Background Induced D-D fusion,” in *fifth International Conference on Emerging Nuclear Energy Systems, ICENES '89*, Karlsruhe, Germany, 1989.
[28] I. Dardik, H. Branover, A. El-Boher, D. Gazit, E. Golbreich, E. Greenspan, A. Kapusta, B. Khachatorov, V. Krakov, S. Lesin, B. Michailovitch, G. Shani, T. Zilov, “Intensification Of Low Energy Nuclear Reactions Using Superwave Excitation in *Tenth International Conference in Cold Fusion (ICCF-10)*, Massachusetts, Cambridge, 2003.
[29] P. L. Hagelstein, D. Letts and D. Cravens, “Terahertz Difference Frequency Response of PdD in Two-laser Experiments,” *Journal of Condensed Matter Nuclear Science,* p. 59–76, Vol. 3 July 2010.

[30] S. Szpak, P.A. Mosier-Boss, F.E. Gordon, Further evidence of nuclear reactions in the Pd lattice: emission of charged particles, Naturwissenschaften 94 (2007) 511–514.
[31] K. Alabin, S. Andreev, A. Sobolev, S. Zabavin, A. Parkhomov, T. Timerbulatov, Isotopic and elemental composition of substance in nickel-hydrogen heat generators, J. Condensed Matter Nucl. Sci. 26 (2018) 32–44.
[32] A.N. Anderson, S.E. Jones, "Comments on an Experiment at Yale on Cold Fusion," in *AIP Conference Proceedings 228*, Provo, Utah, 1991.
[33] P. K. Iyengar and M. Srinivasan, "BARC Studies in cold fusion," Bombay, 1989.
[34] A.G. Parkhomov, R.V. Karabanov, LENR as a manifestation of weak nuclear interactions. New approach to creating LENR reactors, RENSIT 13 (1) (2021) 45–58.
[35] G. Levi, E. Foschi, B. Höistad, R. Pettersson, L. Tegnér and H. Essén, "Observation of abundant heat production from a reactor device and of isotopic changes in the fuel [Preprint]," Lugano, 2014.
[36] C.P. Berlinguette, Y.-M. Chiang, J.N. Munday, T. Schenkel, D.K. Fork, R. Koningstein, M.D. Trevithick, Revisiting the cold case of cold fusion, Nature 570 (7759) (2019) 45–51.
[37] T. Schenkel, A. Persaud, H. Wang, P.A. Seidl, R. MacFadyen, C. Nelson, W.L. Waldron, J.-L. Vay, G. Deblonde, B. Wen, Y.-M. Chiang, B.P. MacLeod, Q. Ji, Investigation of light ion fusion reactions with plasma discharges, J. Appl. Phys. 126 (20) (2019) 203302.
[38] US Patent and Tradmark Office, "US Patent and Tradmark Search," 2021. [Online]. Available: https://uspto.report/company/Industrial-Heat-L-L-C/patents. [Accessed 5 April 2021].
[39] K. Shubber, R. Smith and P. Smith, "The long-shot science that attracted Brad Pitt and Neil Woodford," Finantial Times, 14 June 2019. [Online]. Available: https://www.ft.com/content/024cfc4a-8df6-11e9-a1c1-51bf8f989972. [Accessed 2 April 2021].
[40] M.K. Bradley, C.K. Droney, Subsonic Ultra Green Aircraft Research Phase II: N + 4 Advanced Concept Development, Huntington Beach, California, 2012.